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Pulsed Power and Plasma Science Laboratory

DURIP-97 FINAL TECHNICAL REPORT

Upgrade of a Long Pulse Backward Wave Oscillator to Ultraclean Vacuum Conditions

(Grant No. F49620-97-1-0102)

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Abstract

A brazed ceramic insulator stack has been designed and constructed for use on the University of New Mexico long pulse PI-110A electron beam accelerator that is being used to drive a high power backward wave oscillator. This ceramic insulator stack now establishes an environment within the high power tube that is similar to the environment found in commercially manufactured vacuum tubes such as klystrons. Detailed experiments will follow to establish whether this new environment leads to significant advances in the output energy that is radiated from these type of sources.

Description of Instrumentation

The instrumentation that was proposed to purchase were:

1. Titan/Pulsed Sciences, Inc. complete ceramic insulator stack custom designed and constructed for use on the University of New Mexico's modified PI-110A electron beam accelerator.
2. CTI-Cryogenics Cryo-Torr 8 Metal Seal vacuum pump.
3. MDC Corporation high vacuum electropneumatically-operated gate valves and related components (including metal gasket-compatible flanges).

All of these items have been delivered to the University of New Mexico's EECE Department's Pulsed Power and Plasma Science Laboratory.

Background Information

Advances in high peak power microwave source research have in recent years yielded devices capable of generating peak power levels exceeding 1 GW [1-4]. Unfortunately, the progress achieved in radiating larger peak power levels has been tempered by a decrease in the width of the radiated power pulse, the so-called "pulse shortening" problem [5]. This observation of minimal increase in radiated microwave energy with an increase in radiated peak power levels is apparent across all classes of high power microwave sources. The unintentional introduction of plasma has long been suspected as a factor leading to pulse shortening [6].

Surface treatment is a well-known technique to improve the high voltage hold-off characteristics of HPM sources. Generally, conditioning the microwave producing structures increases both the output power and pulse duration. This is attributed to induced outgassing and/or removal of microprotrusions at the wall surfaces. In earlier work at the University of New Mexico, 100 nm thick TiO_2 and 150 nm thick Cr coatings were evaporated onto the walls of the microwave producing slow wave structure (SWS) of a backward wave oscillator (BWO). These coatings have a low secondary electron emission yield and they have been shown to effectively suppress multipactor in cavities and on rf windows of klystrons and accelerators [7- 9].

In experiments that studied HPM generation in a long pulse intense beam-driven BWO, the radiated pulse duration increased by 50% (from 100 ns to 150 ns) for slow wave structures coated with TiO_2, and by 30-60% for slow wave structures coated with Cr. In both cases improved performance was achieved after several (10s to 100) conditioning shots. The coatings did not affect the maximum power amplitude of the microwave pulse (on the order of 100 MW) compared with experiments that used uncoated structures; the radiated energy increased.

Upgrade of accelerator to high vacuum conditions: hybrid hard tube technology

The results of the earlier experiments that utilized thin film coatings of various composite materials suggested that vacuum and surface conditions inside the high power microwave cavities play an important role in the operation of the device. Clearly this has been appreciated by the commercial vacuum tube community, and this is an issue that the pulsed power community has begun to recognize (see, for example, the exhaustive treatment by Cuneo, et al. [10].

All pulsed power high power microwave sources studied to-date have used technology that did not consider the vacuum and surface conditions within the devices. This has been true with other pulsed power experiments (as discussed in Cuneo et al.). However, as the energy densities involved continue to increase, vacuum and surface conditions become a consideration. In order to better study this issue several researchers are attempting to invoke so-called "hybrid hard tube" technology. This includes the joint work between the Air Force

Research Laboratory-Phillips Research Site and SLAC on a hard tube MILO, work at Los Alamos National Laboratory on a hard tube RKA, and three university efforts, one at the University of Michigan, another at Cornell University, as well as the present work at the University of New Mexico.

In our work, the University of New Mexico has upgraded its long pulse electron beam accelerator by eliminating all plastic components (such as the grading ring stack in the oil/vacuum interface) and replacing them with a bazed ceramic insulator stack (see Fig. 1). Furthermore, all o-ring seals are being replaced with copper gaskets, and the evacuation of the tube will be accomplished using oil-free primary pumps and cryopumps. These measures will establish an environment within the HPM tube that is consistent with the environment inside commercial sealed tubes. Coupled with active cleaning and baking, it is expected that considerable improvement in device performance will result.

Pulse Shortening Diagnostics

The initial attempt at understanding pulse shortening in the UNM BWO was simple beam current density probes. An overview of the possible causes of pulse shortening has been provided by Benford and Benford [5], and one of the suspects was degraded coupling of the electron beam with the electromagnetic modes of the electrodynamic structure. Previous researchers [11] had observed the broadening of an intense relativistic electron beam during microwave generation in a Cerenkov device.

Indeed, when a radial array of current measuring devices was implemented in the UNM device, beam broadening was observed. A detailed description of these measurements is found in [12]. A current probe was placed at two positions in the SWS in two different experiments: (i) in the middle of the SWS without microwave production and (ii) at the end of the SWS with high power microwaves. The electron beam is generated by explosive field emission from an annular knife-edge graphite cathode with a radius of 10 mm. At 12 cm downstream from the cathode, in the middle of the SWS, the electron beam showed a uniform annular electron beam distribution at a radius of 10 mm for more than 200 ns. With microwaves, at 17 cm downstream from the cathode, the profile of the electron beam begins to seriously degrade 180 ns after emission started. At that time, the beam appears to split into two separate annuli centered at radii of 9 mm and 11 mm. Benford and Benford hypothesize that this broadening can be attributed to **ExB** drifts of electrons. Other possible explanations involve the turbulently enhanced resistivity of the background plasma (ionized material emanating from the cavity walls) affecting the beam electrons. In any event, it is still unknown whether the broadened beam distribution leads to poor coupling with modes, thereby quenching the microwave generation mechanism, or whether the beam distribution is affected by the intense microwave fields and pulse shortening is attributed to a microwave discharge. To better understand this problem a laser interferometry measurement was performed.

The first direct measurements of the plasma electron density during the course of microwave generation in a high power vacuum backward wave oscillator have been performed with a HeNe laser interferometer at the University of New Mexico. The basic experimental apparatus is described in detail in references [13-15], and thus, is only briefly summarized here.

The optical arrangement of the Michelson laser interferometer is shown in Fig. 2. A detailed description of the laser interferometer setup is given in [15]. A HeNe laser beam passes through a 35 mm diameter optical window into the SWS radially located between the relativistic electron beam and the wall of the SWS. The optical port does not influence microwave extraction since most of the microwave power density is located outside of the optical window region, consistent with the TM_{01} mode. The response time of the interferometry system is 8 ns. A gold-coated stainless steel mirror ring is placed adjacent to the cut-off neck in the SWS, and serves as a reflector for the laser interferometer, as well as the electrical boundary for the microwave field. The mirror ring is matched to the dimension of the cut-off neck which has an inner diameter (ID) of 23 mm, whereas the annular electron beam is positioned between $r = 9\ mm$ and $r = 11.5\ mm$. The SWS consists of a 10 period stainless steel structure with an ID of 25.55 mm and a total length of 147 mm. A 19 mm spacer, designed to protect the optical mirror from the anticipated blow-off of material ejected from the SWS during the course of microwave generation, is placed between the mirror and the stainless steel rings. Previous measurements with spacers in front of the cut-off neck demonstrated that a shift of 0.5 l_g (e.g., which equals 19 mm, where l_g is the wavelength in the waveguide) does not influence the output of the high power BWO [16].

The results of the laser interferometer measurements are shown in Figs. 3 and 4. In general, two phases of the line-integrated electron density have been measured by the interferometer. The initial or first phase is characterized by a linear increase in plasma density and can only be detected on a very sensitive scale. This plasma is first observed at a time corresponding to the onset of the electron beam current in the SWS. This is indicated in Fig. 3, which shows the line integrated electron density on a time scale of interest for microwave generation, i.e. 50 ns/div. The linear rise in line-integrated electron density continues until about 200 ns after the onset of the electron beam current, at which point the second phase in the measurement begins, as indicated in Fig. 4. Note that this measurement is on a less sensitive amplitude scale, and much longer time scale than the measurement in Fig. 3b. (The features in Fig. UNM-3b are barely visible as the rising portion of the signal in Fig. 4.) At approximately $t = 200\ ns$, $<n_e L>$ suddenly increases very dramatically until it reaches its maximum at about $t = 400\ ns$, as shown in Fig. 4. This enormous increase in plasma is measured after the termination of the microwave pulse. However, this can be attributed to plasma originating along the SWS wall and diffusing radially inward across the magnetic field lines into the path of the laser beam.

This characteristic of plasma appearing in two phases occurs on all of the measurements taken during this study [15]. Furthermore, an increase of phase I and phase II plasma densities correlates with a decrease in the radiated microwave pulse duration. The line-

integrated plasma density in phase II is about one order of magnitude greater than the plasma generated in phase I, and the phase I and II plasma densities are roughly proportional to each other.

To help understand the role that these two phases of plasma formation play in pulse shortening in this high power BWO, an additional set of measurements was taken without the SWS in order to determine how the intense electron beam by itself can contribute to the plasma electrons measured in the propagation region. The 10 ring periodic structure was replaced with a stainless steel tube with an ID of 32 mm and the electron beam propagated through this system. (No microwaves are generated in this case.) When the laser beam is located close to the inner edge of the mirror, the start of the phase I plasma corresponds to the beginning of the electron beam current. In addition, the measured electron plasma is delayed and is smaller in amplitude when the laser beam is positioned closer to the outer edge of the mirror, The conditioning effect has been also observed with the tube structure (i.e., without microwave generation) for the phase I plasma.

The interpretation of all measurements taken during the course of this study is as follows. The electron beam scrapes along the wall of the cut-off neck and produces plasma that rapidly diffuses along the magnetic field lines into the SWS (the phase I plasma). The measurements indicate that the presence of intense microwaves further increases the phase I plasma density. Moreover, an increase in damage at the inner edge of the optical mirror is observed after a single shot with intense microwaves. Minimal damage is observed on the mirror after many shots using the smooth-walled waveguide instead of the SWS. (The effects of the background gas on the interferometry signal can be neglected since total ionization of the gas would result in a line-integrated electron density on the order of 10^{14} cm^{-2}.) The plasma from the beam dump can be discounted as a significant source to these measurements since the electron beam is less intense at that point, and a novel recessed beam dump with screen mesh shielding is used to suppress plasma expansion [14]. Also, the beam dump has an ID of 50 mm, compared to the walls of the SWS with an ID of 25.55 mm; thus, plasma from the beam dump cannot drift into the SWS in time to cause microwave pulse shortening. We believe that the phase II plasma, which is measured to be an order of magnitude greater in amplitude than the phase I density, is probably the plasma following a catastrophic event, such as a microwave field-initiated breakdown in the SWS. This plasma is also correlated with the microwave pulse duration. This assumption is supported by earlier work [14] where low energy electrons were measured by a Faraday cup near the SWS walls during microwave generation. The 200 ns delay in measuring this plasma is attributed to the plasma having to cross magnetic field lines in order to be accessed by the laser measurement. Moreover, it is likely that this plasma is created at the peak of the microwave power pulse when the electric fields are the greatest.

To minimize electron beam scraping, the cut-off neck has been replaced with a bragg reflector [17, 18] (see Fig. 1). Initial measurements confirmed that electron beam scraping along the walls of the reflector has been significantly reduced. Moreover, the reflection coefficient of the bragg reflector is higher than that of the cut-off neck. The disadvantage of the bragg reflector is the position of reflection (i.e., at the center of the first cavity), which

causes a frequency dependent phase shift for the reflected wave. Further research is required to ascertain the ultimate improvement gained by using a Bragg reflector in an intense beam–driven BWO.

The results presented in this section argued for providing an environment for the operation of the high power microwave tube that could minimize the introduction of unwanted plasma in the electrodynamic structure.

Description of Ceramic Insulator Stack

Electrical Design

The electrical design was based on similar insulators that have been demonstrated to be reliable on laboratory pulsers operating in the region of 10^{-6} to 10^{-7} Torr.

The electrical design criteria included electric field stress in the insulator and on the cathode stalk, uniform grading along the insulator stack, triple point shielding in vacuum, and maximizing the field emission thresholds on conductor surfaces.

The design value for electric field (average) in the ceramic was chosen to be 14 kV/cm based on the experience of the LBNL Heavy Ion Accelerator insulator and the NRL HPM insulator. The LBNL insulator in the diode region typically runs at 14 kV/cm for 4 microsecond pulses and has been tested to over 16 kV/cm without flashover. Microwave tube manufacturers indicate that 20 kV/cm is a standard design value for their products. However, microwave tubes generally operate at $< 1\text{x}10^{-8}$ Torr and require substantial vacuum and voltage conditioning. The insulator designed and constructed for UNM will operate reliably in the 10^{-6} to 10^{-7} Torr range.

The cathode stalk geometery has a vacuum impedance in the insulator region of approximately 60 Ω. This value was chosen to minimize the electric field on the stalk. At 800 kV operation this translates to 220 kV/cm.

Anodized aluminum has a demonstrated electron emission threshold above 200 kV/cm for 1 microsecond pulses without conditioning. The outgassing characteristics of anodized aluminum ($8\text{x}10^{-8}$ Torr-liters/s/cc) make it unattractive for ultrahigh vacuum operation. The emission threshold for stainless steel varies according to its preparation. For microsecond pulses bare stainless steel cathode field operating levels are about 100 kV/cm. Electropolishing and hydrogen firing (greening) tend to improve the emission threshold. A reasonable design value for stainless steel that was used was 200 kV/cm. The grading of the insulator assembly was accomplished by using load resistors that surround the ceramic insulator and a metal roll-up attached to the cathode plate on the oil side as well as by gradient rings between ceramic segments on both the vacuum and oil sides. The gradient ring design also shields the triple-points where the ceramic, metal and vacuum are contiguous.

Future Work

An intense period of experimental investigation will commence in the summer 1999. All pulse shortening diagnostics described earlier will be implemented to assess the effects of the upgraded accelerator on radiated microwave energy. A variety of active cleaning and conditioning techniques such as bake-out, plasma cleaning, etc. will be considered. The results of these studies will be fully documented in publications.

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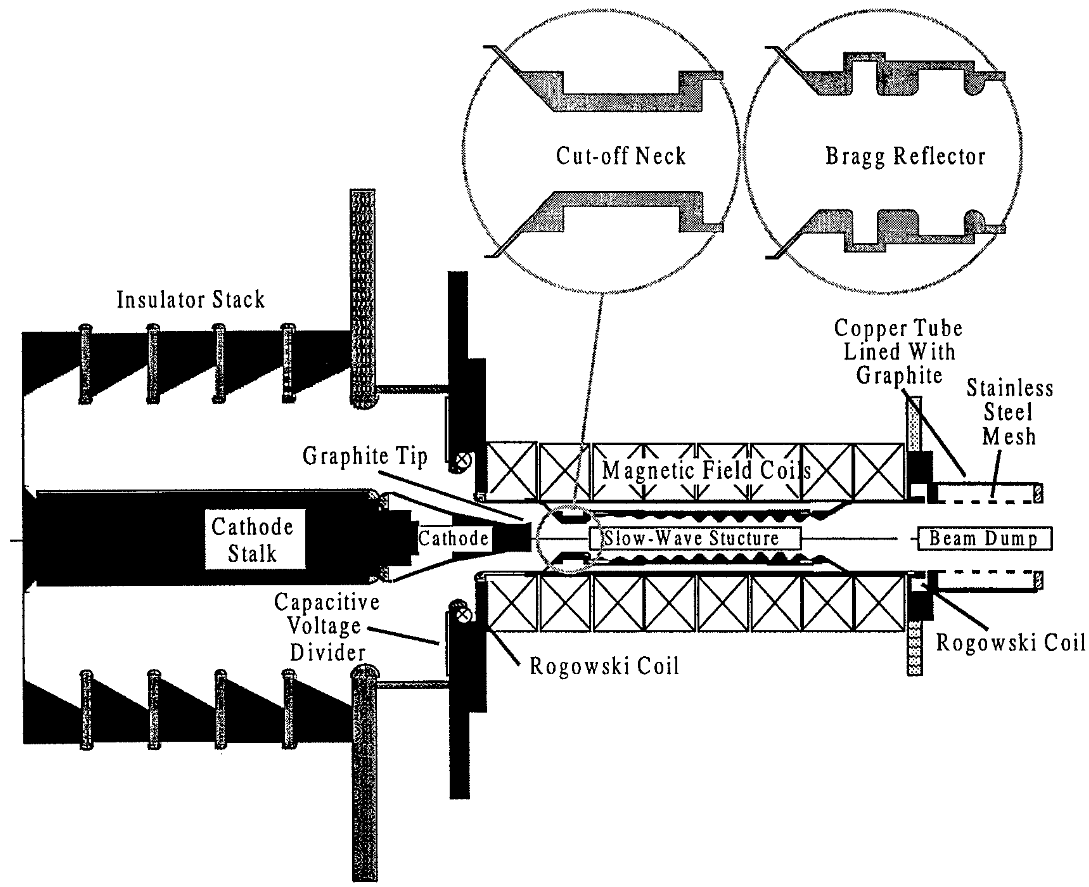


Figure 1. Cross-sectional diagram of the BWO showing the ceramic insulator stack and the updated inlet configuration.

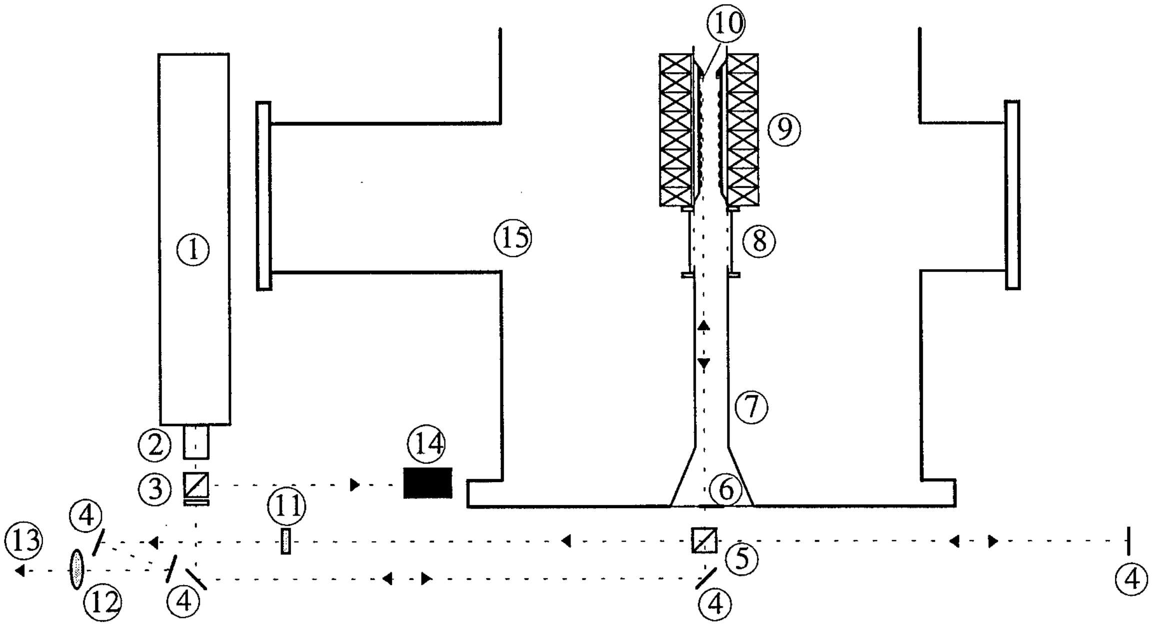
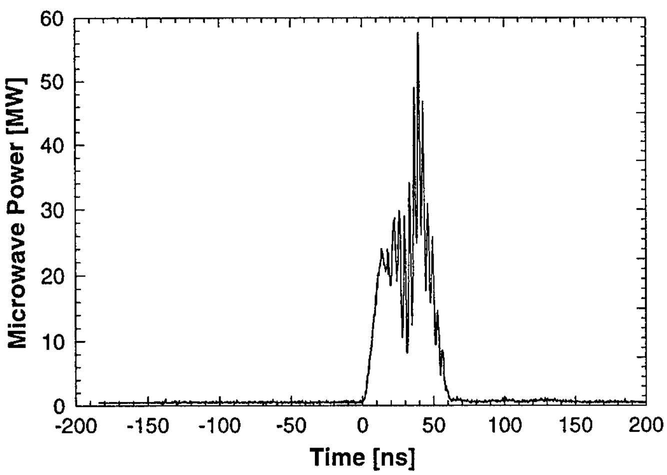


Figure 2. Optical arrangement of the Michelson laser interferometer. 1) 25 mW HeNe laser, 2) 3X beam expander, 3) polarizing beamsplitter and quarter-wave plate, 4) dielectric HeNe laser mirror, 5) non-polarizing beamsplitter, 6) optical window enclosed by Mylar, 7) conical horn antenna, 8) electron beam dump, 9) SWS encircled by magnetic field-producing solenoids, 10) mirror in the SWS, 11) laser line filter, 12) lens, 13) toward laser detector, 14) laser beam dump, and 15) vacuum vessel of the BWO.



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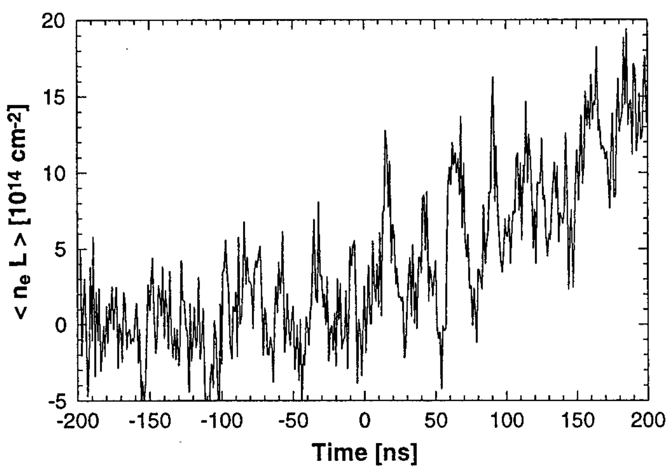

(b)

Figure 3. Typical results of (a) the microwave signal and (b) the early phase of the line-integrated plasma density (i.e., phase I plasma). Generally, $t = 0$ corresponds to the start of the microwave signal

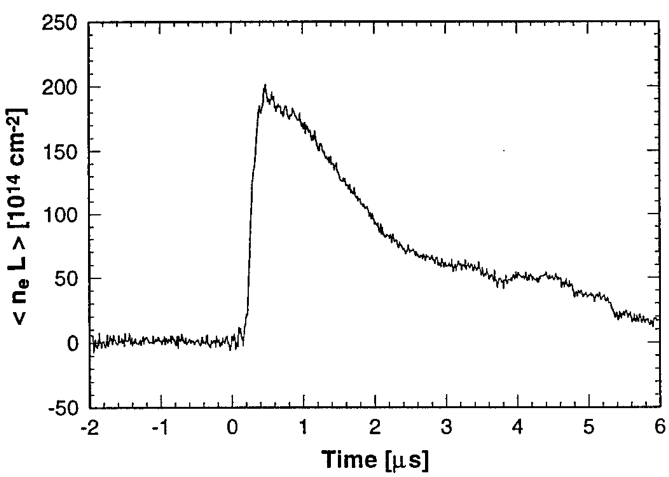

Figure 4. Typical line-integrated plasma density signal on a longer time scale. The maximum plasma density is measured 200 ns after the termination of the microwave pulse (i.e., phase II plasma). Generally, $t = 0$ corresponds to the start of the microwave signal.